SINGLE-POLARISATION OPERATION OF HIGHLY BIREFRINGENT BOW-TIE OPTICAL FIBRES

Indexing terms: Optical fibres, Birefringence

Experimental results show that bow-tie fibres with high levels of stress-induced birefringence can be operated such that they support only a single linearly polarised mode. Under these conditions the loss of the fibre is 5 dB/km for the guided mode and 55 dB/km for the suppressed mode. For short-length operation as a polariser, extinction ratios as high as 50 dB/m have been obtained.

Introduction: Highly birefringent fibres are of considerable interest in the fields of optical fibre sensors and coherent detection systems because they can transmit stable, linearly polarised light. Birefringence is usually induced in the fibres by exploiting the thermal stress produced by high-expansion regions incorporated within the cladding. Maximum birefringence is achieved by employing a cross-sectional geometry resembling a bow-tie, as used in the bow-tie (MCVD)[1] (see inset of Fig. 2) and PANDA (VAD)[2] fibres. The polarisation-maintaining property of the fibres relies on exciting only one of the two orthogonal, linearly polarised modes in the hope that no coupling occurs to the other mode. How well the fibre performs depends on the birefringence (i.e. the propagation constant spacing $\Delta\beta$ between the modes) and the severity of the external perturbations. Under ideal conditions, an output polarisation extinction ratio of 20 dB after 5 km of PANDA fibre has been reported.[2]

An altogether more satisfactory solution to the transmission of linearly polarised light would be to suppress one of the two linearly polarised modes such that only one polarised mode can propagate. Two approaches to achieve this have been described theoretically, namely the side-pit[3] and stress-guidance[4] fibres. While the first has not been successfully demonstrated, the second has been achieved in our laboratories, although with relatively low NA.

Recently, however, the waveguide theory relating to material birefringence in optical fibres has beeen formulated,[5] and the results indicate that fibres having sufficient stress-birefringence can be operated such that one polarised mode is heavily attenuated, i.e. the fibre acts as a polariser. In this letter we briefly outline the mechanism involved and present experimental results for the bow-tie fibre. It is shown that these fibres have a low-loss region in which one polarised mode can propagate while the other is leaky. Different operating modes exist, depending on whether the fibre is to be used in short lengths as a high-exinction polariser, or in long lengths for transmission of linearly polarised light.

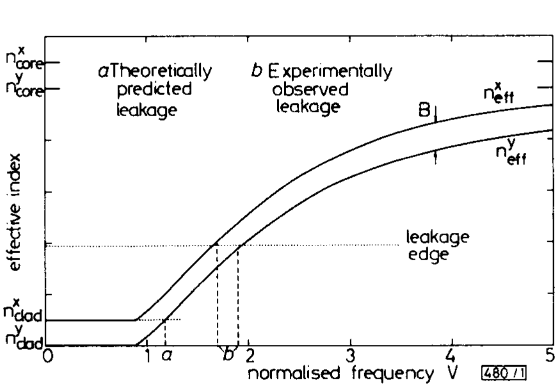

Fig. 1 *Effective index against normalised frequency for x- and y-polarised modes of a monomode fibre having stress-induced birefringence*

Also shown are V-values for which equivalent index of y-polarised mode falls below that of x-polarised cladding index resulting in mode leakage. Effective index at which experimental fibre modes were observed to leak are indicated

Theory: Fig. 1 shows the effective index β/k against normalised frequency V diagram for a monomode fibre having modal stress birefringence B, where

$$B = \frac{\lambda}{L_p} = n^x_{core} - n^y_{core} = n^x_{clad} - n^y_{clad} \tag{1}$$

and n^x and n^y are the refractive indices seen by light polarised in the x and y directions, respectively. Here L_p is the beat length between the x and y polarised modes. We have assumed that the material anisotropy affects the core and cladding of the fibre equally, and thus x and y polarised light see two identical index profiles slightly shifted with respect to each other. For high V-values the effective index of each mode lies close to that of their respective cores, while for low V-values it falls to that of their respective claddings. We have chosen to scale the graph so that $B = 0{\cdot}1 \times (n^x_{core} - n^y_{core})$, since the results presented here are for a bow-tie fibre having a beat length of 1·2 mm at 633 nm and having $\Delta n = n^x_{core} - n^x_{clad} \simeq 5 \times 10^{-3}$.

Snyder and Ruhl[5] have shown that the condition for suppression of the mode polarised in the y direction is that its effective index n^y_{eff} should lie below the cladding index of the x-polarised mode, i.e. $n^y_{eff} < n^x_{clad}$. At all V-values below that corresponding to $n^y_{eff} = n^x_{clad}$, the y-polarised mode leaks, as indicated in Fig. 1. In practice, both the x and y polarised modes become leaky at small V-values, giving rise to the commonly observed long-wavelength microbending edge, particularly in fibres having a depressed cladding. However, the microbending edge will occur at higher V-values for the y-polarised mode than for the x-polarised mode, since both microbending edges will occur when the effective index of the respective mode is at about the same level above n^x_{clad}.

Results: Fig. 2 shows the attenuation (dB/km) as a function of wavelength for the x and y polarised modes of a bow-tie fibre. The fibre was 500 m long, had a beat length of 1·2 mm at 633 nm and a second-order mode cutoff at 600 nm ($V = 2{\cdot}4$). The wavelength edges at which the x- and y-polarised modes leak are separated by 100 nm, and operation of the fibre within this region will result in considerable differential attenuation between modes. For example, at 830 nm a 5 dB/km loss is sustained by the guided mode, while the leaky mode experiences 55 dB/km. Thus the fibre exhibits both low loss and an extinction ratio of 50 dB/km.

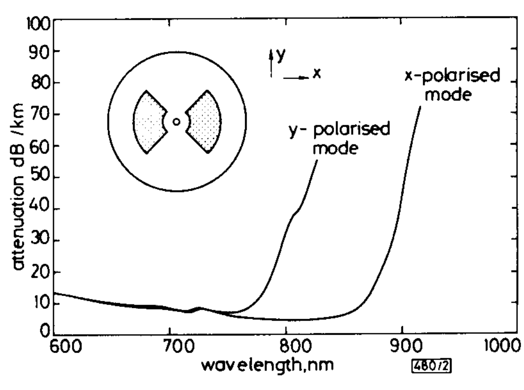

Fig. 2 *Attenuation characteristics as a function of wavelength of x- and y-polarised modes measured in 500 m of bow-tie fibre*

The solid line in Fig. 3 shows the extinction ratio (dB/m) as a function of wavelength in 0·5 m of the same bow-tie fibre. The maximum extinction ratio measurable with our monochromator/polariser system was about 25 dB, and this occurred at 920 nm ($V = 1{\cdot}6$). At this wavelength both modes experience leakage attenuation (see Fig. 2); however, the differential attenuation is extremely large and leads to remarkably high extinction ratios in short lengths. Used at this wavelength the fibre makes an ideal polariser having an insertion loss of <0·5 dB/m for the guided mode.

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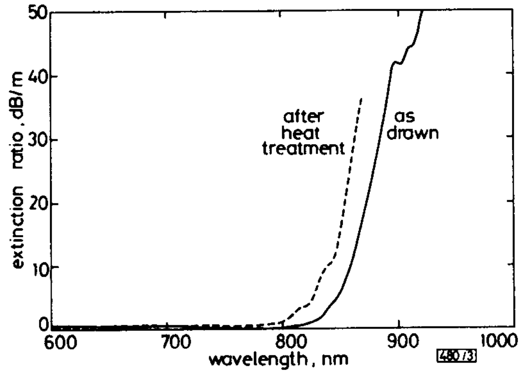

Fig. 3 *Extinction ratio of a 0·5 m length of bow-tie fibre measured as a function of wavelength*

Effect of increasing fibre birefringence by heat treatment is also shown

The broken line in Fig. 3 shows the extinction ratio of the fibre after its beat length was reduced to 0·8 mm by thermal annealing.[6] It can be seen that annealing enhances the polarising performance of the fibre, since it results in a greater separation between the wavelengths at which leakage occurs, thus increasing the differential modal attenuation.

Discussion: It can be seen from the curves in Fig. 2 that the leakage edges for the x- and y-polarised modes occur at 860 nm and 760 nm, corresponding to $V = 1{\cdot}7$ and $1{\cdot}9$, respectively. These values are considerably higher than the leakage edge predicted theoretically ($V = 1{\cdot}2$), suggesting that a mechanism exists whereby the modes leak prematurely. This is borne out by our experimental observation that the leakage edges could be shifted in wavelength by bending the fibre. The effect is probably related to the proximity of the stress-producing sectors which have a depressed index, giving a W index profile in one direction. A recent report[7] suggests a similar mechanism. However, a number of bow-tie fibres with different geometries, and an elliptical jacket[8] fibre with a cladding approximately matched to the silica substrate, have been measured and found to behave similarly. Nonetheless, if we assume that the bow-tie fibre behaves as a step-index monomode fibre (Fig. 1) we see that the leakage occurs at the same effective index for both modes, indicating that the leakage mechanism is similar in each case.

Conclusions: Stress-birefringent fibres operated at V-values of around 1·8 can exhibit large differential attenuations between the two orthogonally polarised modes due to mode leakage. In a bow-tie fibre where the birefringence is sufficiently high, a wavelength region exists where the guided mode loss is less than 5 dB/km, while the leaky mode losses can be as large as 55 dB/km. At longer wavelengths where the guided mode loss is $<0{\cdot}5$ dB/m, the polarisation extinction ratio exceeds 50 dB/m. The latter effect has been observed experimentally in elliptical-jacket stress-birefringent fibres, as well as in a number of bow-tie fibres. The fibres will find application whenever truly single-mode single-polarisation operation is required.

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References

1 BIRCH, R. D., PAYNE, D. N., and VARNHAM, M. P.: 'Fabrication of polarisation-maintaining fibres using gas-phase etching', *Electron. Lett.*, 1982, **18**, pp. 1036–1038
2 SASAKI, Y., OKAMOTO, K., HOSAKA, T., and SHIBATA, N.: 'Polarisation-maintaining and absorption-reducing fibres'. Opt. Fib. Conf., 1982, pp. 54–56
3 OKOSHI, T.: 'Single polarisation, single-mode optical fibres', *IEEE J. Quantum Electron.*, 1981, **17**, pp. 879–884
4 EICKHOFF, W.: 'Stress-induced single-polarisation single-mode fibre', *Opt. Lett.*, 1982, **7**, pp. 629–631.
5 SNYDER, A. W., and RUHL, F.: 'New single-mode, single-polarisation optical fibre', *Electron. Lett.*, 1983, **19**, pp. 185–186
6 OURMAZD, A., BIRCH, R. D., VARNHAM, M. P., PAYNE, D. N., and TARBOX, E. J.: 'Enhancement of birefringence in polarisation-maintaining fibres by thermal annealing', *ibid.*, 1983, **19**, pp. 143–144
7 KATSUYAMA, T., MATSUMURA, H., and SUGANUMA, T.: 'Low-loss single-polarisation fibres', *ibid.*, 1981, **17**, pp. 473–474
8 Laser Focus, Feb. 1983, pp. 77

0013-5194/83/070246-02$1.50/0